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Fault feature extraction of rolling element bearings using sparse representation

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ABSTRACT

Influenced by factors such as speed fluctuation, rolling element sliding and periodical variation of load distribution and impact force on the measuring direction of sensor, the impulse response signals caused by defective rolling bearing are non-stationary, and the amplitudes of the impulse may even drop to zero when the fault is out of load zone. The non-stationary characteristic and impulse missing phenomenon reduce the effectiveness of the commonly used demodulation method on rolling element bearing fault diagnosis. Based on sparse representation theories, a new approach for fault diagnosis of rolling element bearing is proposed. The over-complete dictionary is constructed by the unit impulse response function of damped second-order system, whose natural frequencies and relative damping ratios are directly identified from the fault signal by correlation filtering method. It leads to a high similarity between atoms and defect induced impulse, and also a sharply reduction of the redundancy of the dictionary. To improve the matching accuracy and calculation speed of sparse coefficient solving, the fault signal is divided into segments and the matching pursuit algorithm is carried out by segments. After splicing together all the reconstructed signals, the fault feature is extracted successfully. The simulation and experimental results show that the proposed method is effective for the fault diagnosis of rolling element bearing in large rolling element sliding and low signal to noise ratio circumstances.

1. Introduction

Rolling element bearings are critical components of rotating machinery, and it's important to monitor their condition to avoid catastrophic failures in modern machinery. A rolling element bearing usually consists of an inner race, an outer race, rollers and a cage. If a local damage develops on the surface of any of these components, the strikes of rollers on the fault surface will excite the resonant frequencies of structures between the bearing and the transducers, and trigger the periodical impulses which are characterized by modulation phenomenon [1,2]. The impulse response signal can be collected by transducer installed on the bearing pedestal accompanied by other structure vibration and noise. How to extract the impact signal accurately is a key issue of fault diagnosis of bearing.

In the past twenty years, signal sparse representation theory [3] has received considerable attentions and made remarkable achievements in the field of image processing [4], speech recognition [5] and compressed sensing[6,7]. This

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theory is also be used for fault feature extraction and signal separation in rotating machinery recently. The foundation of the sparse representation is to construct signal based on a linear combination of basis functions or atoms. There are two key issues related to sparse representation: redundant dictionary design and sparse coefficients solving. In order to match the local structure of signal, the dictionary must be carefully designed; the more similar the dictionary's atom and the structure of signal are, the more quickly and accurately the analyzed signal will be sparsely represented. For extracting the impact caused by bearing fault using the sparse decomposition, many works focused on how to construct dictionary which has similar structure with the analyzed signal. For example, Liu et al. [8] employed matching pursuit with time-frequency atoms to analyze bearing vibration and extract vibration signatures, and proved that the method worked better than continuous wavelet transform and envelope detection. Cui et al. [9] established a new impulse dictionary according to the characteristics of rolling bearing, and matching pursuit using the new dictionary combined with genetic algorithm was used for bearing fault diagnosis. Using the redundant Fourier basis, identity matrix basis and short-time Fourier basis, Qin et al. [10] constructed a composite transform basis dictionary and vibration signal components of faulty machine were separated by iteratively using basis pursuit algorithm. Zhu and Cai [11,12] employed Laplace wavelet, Morlet wavelet, tunable Q-factor wavelet successively to construct the redundancy dictionary, and fault features of rotating machines were extracted by the split augmented Lagrangian shrinkage algorithm (SALSA) combined with neural network. Tang et al. [13] employed shift-invariant sparse coding (SISC) algorithm for dictionary learning, and the underlying structure of machinery fault signal was captured by sparse representation based on latent components decomposition method. Liu et al. [14] optimized atom parameters using spectrum kurtosis and smoothing index, and the faulty impulse period was matched by correlation matching method based on optimized atom.

Although sparse representation has been used for diagnosing bearing fault successfully, there is still much work to do, and the following situations still need to be considered.

(1) When a localized defect is induced, repeat impacts will be generated due to the passing of rolling elements over the defect. The wide-band energy of the impacts will evoke several modes of resonance of the bearing elements, the structure and the sensor. But most dictionaries constructed in literature only use one natural frequency. There is no guarantee that these dictionaries will match the structures of the analyzed data well.
(2) For inner race and rolling element faults, the amplitudes of the defect-induced impulses vary as the inner race or rolling element defects enter and leave the bearing load zone [15,16]. Taking the transmission path and the projection direction of the impulse force into further consideration, the amplitudes of the impulse forces may be smaller or even harder to detect when the defect is out of the bearing load zone. For simplicity, most literature did not take the impulse missing into consideration in sparse coefficients solving.
(3) The slippage of rolling element and the fluctuation of rotational speed may cause random variation in spacing between two consecutive defect-induced impulses in practice [17]. But most literature diagnosed the bearing fault by using sparse decomposition based on the consideration of equal-spaced generation of force impulses, and the periodically time-varying statistics characteristic of the vibration of rolling element bearing was neglected.

To extend the suitability of sparse representation theory on bearing fault diagnosis, the above situations should be taken into consideration. In this paper, the natural frequencies and relative damping ratios of the bearing system are identified by correlation filtering method. The obtained waveform parameters are put into the impulse response function of damped second-order system to construct the redundant dictionary. Considering impulse missing and rolling elements sliding situations, the fault signal is divided into segments before sparse coefficient solving, and the defect-induced impulses are constructed by segments. After splicing together all the reconstructed segments, the averaging interval of the identified impulses is obtained and bearing fault can be diagnosed accordingly.

The remainder of this paper is organized as follows: In Section 2, the principles of matching pursuit is briefly introduced. In Section 3, dictionary construction method based on correlation filtering is given, and a new bearing fault detection method using sparse representation with the designed dictionary is proposed. The effectiveness of the proposed method is verified by simulation in Section 4 and assessed by experimental results in Section 5. Finally, conclusions are drawn in Section 6.

2. The basic principles of matching pursuit

Matching pursuit is a commonly used algorithm for sparse representation [18], and the principle of matching pursuit lies in decomposing a signal x into the linear combination of basis functions $\boldsymbol{d}_\gamma(\|\boldsymbol{d}_\gamma\|=1)$ that belong to a redundant dictionary $\boldsymbol{D}\in R^{n\times q}$. After greedy search, an atom $\boldsymbol{d}_{\gamma 0}\in\boldsymbol{D}$ that best matches the signal structure is selected, and the signal $\boldsymbol{x}$ can be decomposed into

$$\boldsymbol{x}=|\langle\boldsymbol{x},\boldsymbol{d}_{\gamma 0}\rangle|\boldsymbol{d}_{\gamma 0}+R_1\boldsymbol{x} \tag{1}$$

where $\langle\bullet\rangle$ means inner product, R_1x is the residue after the first matching. For the orthogonality of $\boldsymbol{d}_{\gamma 0}$ and R_1x, we get

$$\|\boldsymbol{x}\|^2=\|\langle\boldsymbol{x},\boldsymbol{d}_{\gamma 0}\rangle\|^2+\|R_1\boldsymbol{x}\|^2 \tag{2}$$